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Effect of Trailing Intensive Cooling on Residual Stress and Welding Distortion of Friction Stir Welded 2060 Al-Li Alloy

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Abstract: Trailing intensive cooling with liquid nitrogen has successfully applied to friction stir welding of 2 mm thick 2060 Al-Li alloy. Welding temperature, plastic strain, residual stress and distortion of 2060 Al-Li alloy butt-joint are compared and discussed between conventional cooling and trailing intensive cooling using experimental and numerical simulation methods. The results reveal that trailing intensive cooling is beneficial to shrink high temperature area, reduce peak temperature and decrease plastic strain during friction stir welding process. In addition, the reduction degree of plastic strain outside weld is smaller than that inside weld. Welding distortion presents an anti-saddle shape. Compared with conventional cooling, the reductions of welding distortion and longitudinal residual stresses of welding joint under intense cooling reach 47.7 % and 23.8 %, respectively.

Keywords: friction stir welding, trailing intensive cooling, plastic strain, residual stress, welding distortion

Introduction

2060 Al-Li alloy belongs to the third-generation of aluminum-lithium alloys and is considered to own a promising application prospect in aircrafts due to its high strength, excellent low temperature property and good corrosion resistance [1, 2, 3]. Added Li element brings lots of advantages for aluminum alloys, such as decreasing density and increasing elasticity modulus [4]. Although 2060

Al-Li alloy owns above-mentioned advantages, the defects such as low joint efficiency, porosity and solidification crack still exist when conventional fusion welding techniques are used [5, 6]. Therefore, conventional fusion welding methods are not well applied to 2060 Al-Li alloy.

Friction stir welding (FSW) is a new solid-state joining process, invented in 1991 at The Welding Institute of UK [7, 8]. FSW with low heat input has great advantages for joining Al-Li alloy because not only the volatilization of Li element but also conventional fusion welding defects can be avoided. Therefore, the investigation of Al-Li alloy FSW has been attracting more and more attentions [9, 10, 11].

Prior papers focus on investigating the FSW of Al-Li alloys such as AA2198 [9], AA2050 [10] and AA2199 [11]. To the best of our knowledge, current papers about 2060 Al-Li alloy FSW are few, and the investigations of these papers mainly concentrate on microstructure and mechanical properties of joints. Cai et al. [12] investigated the microstructure and mechanical properties of friction stir welded 2060 Al-Li alloy joint and found that the hardness variation within the welds was related to the dissolution and coarsening sequences of precipitates. Yang et al. [4] further analyzed microstructure and precipitation phase evolution of 2060 Al-Li alloy FSW butt joint and presented that the high temperature precipitated phase Al_xCu_xMn was uniformly distributed throughout the joint. The effect of welding parameters on microstructure and mechanical properties of FSW joints of 2060 Al-Li alloy were studied by Mao et al. [13], and they found that the joints welded at 1180 rpm/118 mm/min owned the highest mechanical properties.

Although FSW produces joints with lower residual stresses than conventional fusion welding, published papers show that significant levels of residual stresses and large distortion still exist, especially for FSW of thin-walled plates [14, 15, 16]. In view of the present research situation, it is of great importance to investigate residual stress and welding distortion for FSW of 2060 Al-Li alloy. To date, some methods of controlling the residual stress and distortion including shot peening

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[17], roller tensioning technique [15] and mechanical tensioning [18] all belong to mechanical methods, which need additional complicated work before or after welding. The published papers point that local thermal tensioning produced by dynamically controlled low stress no distortion (DC-LSND) welding technique can be used to effectively control residual stresses and welding distortion [19]. Moreover, DC-LSND technique avoids additional work before or after welding. The different types of coolants have been used in trailing intensive cooling (TIC)-aided FSW, such as liquid CO₂ [20], CO₂ gas [21] and water [22]. Richards et al. [20] pointed out that the controlling effect depends on the size, power and positioning of the coolants. It is noted that the liquid CO₂ has a better cooling capacity than water as reported by Xu et al. [23]. In particular, the cooling capacity of liquid nitrogen is much higher than that of liquid CO₂ due to the lower coolant temperature. However, up to now, the effect of liquid nitrogen cooling on FSW process has not been reported yet.

In this study, the purpose is to investigate the effect of TIC with liquid nitrogen on FSW joint of 2060 Al-Li alloy. The distribution of temperature, residual stress and welding distortion of butt joint were compared and discussed between conventional cooling and TIC.

Experimental procedures

Two 2060 Al-Li alloy workpieces with dimensions of 200 mm × 188 mm × 2 mm were butt welded by FSW. The chemical composition of 2060 Al-Li alloy is given in Table 1. A tool composed of a 10 mm diameter shoulder and a 1.7 mm length pin and was made of H13 tool steel and used to fabricate the joints. The diameters of pin tip and bottom are 2 and 5 mm, respectively. Experiments were carried out at rotational speed of 800 rpm and welding speed of 80 mm/min [24]. The schematic of TIC during FSW process is shown in Figure 1, in which AS and RS represent advancing side and retreating side respectively. TIC was achieved by directing liquid nitrogen coolant toward the weld top surface through a nozzle positioned at 2 cm behind the tool. The welding parameters under conventional cooling were the same as those under TIC. K-type thermocouples were used in order to attain the

temperature distribution near the weld, verifying the numerical simulation results. The thermocouples were placed at the AS of joint. Distance of the thermocouples from the start edge of workpiece was 60 mm, as shown in Figure 2.

Figure 1: Schematics of the TIC aided FSW.

Figure 2: Schematics of thermocouples locations.

Numerical procedures

Numerical simulation technologies have been used in varied industries due to low cost and visualization of results. In the present study, finite element analysis software ABAQUS/Standard was utilized to understand the temperature field, residual stress field and welding distortion. In fact, temperature difference between AS and RS is produced by different flow direction of material. However, the error can be negligible in numerical simulation owing to minute difference. The identical method was also reported by Jalili et al. [21] and Riahi et al. [25]. Therefore, AS and RS are considered to own the same conditions in this study.

Mesh generation

The dimensions of workpieces in simulation are the same as those in experiment. In order to reasonably

Table 1: Chemical composition of 2060 Al-Li alloy.

Alloy	Cu	Li	Mg	Ag	Zr	Mn	Zn	Al
Wt. %	3.95	0.75	0.85	0.25	0.11	0.3	0.4	Balance

describe the practical welding process, backing plate and pressing plate are both considered in the model, which can be supposed to be thermally conductive rigid body. The finite element model used in this study is shown in Figure 3. Element type of workpieces is DC3D8 brick-8node mesh for coupled temperature and displacement analysis. In order to improve simulation accuracy and save the solution time, finer meshes with size of 1 mm were used near the weld, while meshes away from weld were coarser. Meshes were distributed linearly along the perpendicular direction of the weld. The workpieces are divided into 28,000 elements and consist of 42,813 nodes.

Figure 3: Mesh distribution used in simulation.

Thermal model

Frictional heat model

The auto-adapting thermal model which successfully predicts trends in temperature field and thermal profiles was established by Li et al. [26]. During FSW process, heat input consists of two parts. One is generated by shoulder and the other is generated by pin. The heat generated by friction makes the temperature of workpieces top surface increase, leading to large plastic deformation. Because the H13 tool steel owns higher hardness than aluminum under the same temperature, frictional force is considered to be the product of shear flow stress of aluminum and contacting area. On basis of the above-mentioned principle, the energy balance equation of auto-adapting thermal model can be attained, which mainly depends on yield strength of material and tool rotational speed.

Frictional heat generated between shoulder and workpieces can be written as follows:

$$Q_S = 2\pi\omega 0.577R_{eL}(T)(R_0^3 - r_0^3)/3 \quad (1)$$

where Q_S is shoulder heat input, R_0 is shoulder diameter, r_0 is pin diameter, $R_{eL}(T)$ is yield strength and ω is

angular speed. Heat generated by shoulder is supposed to be surface heat flux with 10 mm diameter.

Frictional heat generated by pin can be written as follows:

$$Q_P = 0.33Q_S \quad (2)$$

where Q_P is pin heat input. Heat generated by pin is simplified as a uniform volume heat flux with 4 mm diameter and 1.7 mm length.

Intensive cooling model

The temperature of liquid nitrogen cooling zone measured by K-type thermocouples is -45°C and barely varies during FSW process. Liquid nitrogen cooling zone is supposed to be surface heat flux with 20 mm diameter in simulation.

Intensive cooling resource can be written as follows:

$$Q_c = 250000 \quad (3)$$

where Q_c is intensive cooling heat input.

Subsequently, these above-mentioned equations are all loaded by the Dflux subroutine of the software ABAQUS.

Heat loss boundary conditions

To accurately predict the temperature distribution, residual stress and welding distortion, the boundary conditions are considered in this study according to the clamping of workpieces in the practical experimental procedure. The methods are essentially in agreement with prior papers reported by Chao et al. [27] and Khandkar et al. [28]. Heat transfer between workpieces and backing or pressing plates could be modeled by contact thermal conductivity. The free convection coefficient was assumed between workpieces and ambient. The ambient temperature was supposed to be a constant value of 20°C . The free convection coefficient was set to be $25 \text{ W}/(\text{m}^2\cdot^\circ\text{C})$. A high value of $100 \text{ W}/(\text{m}^2\cdot^\circ\text{C})$ was applied to describe contact thermal conductivity. The uniform thermal radiation coefficient was assumed to be 0.75. Figure 4 plots the thermal boundary conditions of FSW.

Results and discussion

Figure 5 compares the temperature histories of P1 and P2 (Figure 2) between experimental and numerical simulation

Figure 4: Thermal boundary conditions of FSW.

Figure 5: Temperature histories of conventional cooling aided FSW: (a) P1 and (b) P2.

results during conventional cooling-aided FSW. Results show that the temperature history by numerical simulation

is in good agreement with that by experiment. Temperature of material near weld rapidly rises at the heating stage and quickly drops at the cooling stage. The maximum deviation between experimental and numerical simulation results is about 3 % in the Figure 5a and about 8.4 % in the Figure 5b. Accordingly, the numerical simulation results can be well verified by the experimental results, illustrating the rationality of FE model established in this study.

The temperature distributions of workpieces under the conventional cooling and TIC conditions are shown in Figure 6. The temperature distribution is symmetric with respect to the weld and presents elliptical shape.

Figure 6: Temperature distribution of workpiece: (a) conventional cooling and (b) TIC.

The temperature gradient is high in the front of the tool and low at the rear of the tool. The reason is that the material at the rear of the tool experiences the direct thermal effect of the tool and subsequent thermal conductivity. On the contrary, the material in front of the tool only experiences thermal conductivity. The similar temperature distribution has also been observed by He et al. [29]. The peak temperatures of Figures 6a and 6b are respectively 524.6°C and 493.4°C. Figure 7 compares the high temperature (exceeding 400°C) area through the thickness of joint between the conventional cooling and TIC conditions. It can be seen that the high temperature area of S1 under the conventional cooling is bigger than that of S2 under the TIC. The above results indicate that TIC is beneficial to reduce peak temperature and shrink high temperature area. Compared with conventional cooling, the region behind the tool is directly affected by liquid nitrogen and then owns the lower temperature under TIC. Therefore, more heat transfers from the higher temperature regions toward the region affected by liquid nitrogen, which leads to reduce peak temperature and shrink high temperature area.

Figure 7: High temperature (exceed 400°C) area through the thickness of joint: (a) conventional cooling and (b) TIC.

The plastic strains of outside and center points of weld are shown in Figures 8 and 9, respectively. The positive coordinate of the ordinate shows tensile plastic strain (TPS) and the negative coordinate shows compressive

Figure 8: Distribution of plastic strain of the outside points of weld.

Figure 9: Plastic strain evolution of the center point of weld under different cooling conditions.

plastic strain (CPS). The maximum TPS and CPS both locate near the shoulder is shown in Figure 8. In Figure 9, the plastic strain does not occur at the initial stage of welding. With the approximation of the tool, the CPS of the center point increases gradually, and the maximum value under conventional cooling condition can be achieved when the tool arrives at the point. With the movement of tool, the slow heat transfer was generated between weld and ambient. At the cooling stage, the contraction of metal in weld can be restricted by surrounding metal with lower temperature. Hence, the extra TPS can be achieved along the perpendicular direction of the weld, which contributes to counteract the CPS produced at the heating stage. Under the TIC condition, the materials in and near weld directly affected by intensive cooling can shrink rapidly, leading to generate thermal tensioning on the high temperature metal. Extra plastic deformations are generated between the tool and the intensive cooling source due to thermal tensioning, counteracting the CPS in weld. Accordingly, the plastic strains are reduced obviously when the TIC is used, while the maximum CPS is attained later under TIC than under conventional cooling, as shown in Figure 9. TIC condition can effectively reduce the TPS near the weld and CPS in the weld. However, the reduction degree outside the weld in Figure 8 is smaller than that in Figure 9. This is mainly because that the region outside the weld is only affected by intensive cooling instead of the combination of shoulder and intensive cooling.

Figure 10 compares the distributions of longitudinal residual stress (LRS) under different cooling conditions. It can be seen that LRS presents symmetric M shapes with

Figure 10: Distribution of longitudinal residual stresses of workpiece.

respect to the weld. Based on the distribution of plastic strain (Figure 8), the maximum CPS locates near the edge of shoulder, leading to attain the maximum LRS in the same position. The stress profiles in Figure 10 are in good consistent with the reported study by Lombard et al. [16]. To keep stress balance in the whole workpiece, the LRS changes into compressive residual stress nearby the weld and approaches to zero at the edge of the workpiece.

The maximum LRSes under conventional cooling and TIC conditions are 126 MPa and 96 MPa, respectively. The reduction of LRS achieves 23.8% under TIC condition. Meanwhile, the maximum LRS declines slightly in the center of weld where the LRS values are 100.4 MPa under conventional cooling and 71.4 MPa under TIC. Richards et al. [18] pointed out that the reduction of LRS within the weld resulted from plastic deformation produced by pressure of shoulder. In this study, the reduction of LRS results from the contraction in plastic strains by not only shoulder pressure but also TIC. Accordingly, the reduction in plastic strains and LRS can be beneficial to control the welding distortion.

The welding distortions of workpiece by experiment and numerical simulation are shown in Figures 11 and 12, respectively. It can be seen that the welding distortion is concave in transverse direction and convex in longitudinal direction, looking like an anti-saddle shape. The distortion pattern is in good agreement with Yan et al. [30]. The welding distortions under conventional cooling and TIC by simulation (Figure 12) are similar to those by experiment (Figure 11), which also indicates that the FE model used in numerical simulation of FSW in this study is reasonable. Compared with conventional cooling, the distortion reduces drastically

Figure 11: Distortion of workpiece in experimental results: (a) conventional cooling and (b) TIC.

Figure 12: Distortion of workpiece in simulation results: (a) conventional cooling and (b) TIC.

when the TIC is applied to FSW process. The reason for the decreasing trend is related to the residual stress and plastic strain effectively controlled by TIC. Figure 13 presents the distortion of longitudinal direction by experiment under conventional cooling and TIC. The distortion almost presents symmetric distribution with respect to the weld. The maximum distortions of conventional cooling and TIC are 4.11 mm and 2.15 mm, respectively. The reduction of welding distortion reaches 47.7%. Therefore, the welding distortion can be controlled by applying TIC in FSW process.

Figure 13: Distortion comparisons in experimental results.

Conclusions

The TIC with liquid nitrogen was applied to FSW of 2060 Al-Li alloy. Effect of TIC on temperature field, residual stress and distortion was investigated. Based on the present study, the following conclusions can be drawn.

1. The temperature distribution under TIC is similar to that under conventional cooling. Compared with conventional cooling-aided FSW, the peak temperature and the area of high temperature reduce obviously during TIC-aided FSW process.
2. Plastic strains inside and outside weld reduce when TIC is applied. The reduction degree of plastic strain outside weld is smaller than that inside weld.
3. The maximum LRS values under conventional cooling and TIC are 126 MPa and 96 MPa, respectively. The reduction of residual stress reaches 23.8% by applying TIC in FSW process. The welding distortion shows an anti-saddle shape. The maximum distortion of workpiece under TIC is 52.3% of that under conventional cooling.

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